

New measurements of reactor $\bar{\nu}_e$ disappearance with the Double Chooz far detector



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Outline

I. Experiment overview

II. Latest Double Chooz results

- ▶ Reactor-off background measurements
- ▶ First combined Gd+H fit
- ▶ Reactor rate modulation analysis

III. Future of Double Chooz

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III. Future of Double Chooz

Double Chooz collaboration



Brazil
CBPF
UNICAMP
UFABC



France
APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC
ULB/VUB



Germany
EKKU Tbingen
MPIK
Heidelberg
RWTH Aachen
TU Mnchen
U. Hamburg



Japan
Tohoku U.
Tokyo I. T.
Tokyo Metro.
U.
Niigata U.
Kobe U.
Tohoku Gakuin
U.
Hiroshima I. T.



Russia
INR RAS
IPC RAS
RRC Kurchatov



Spain
CIEMAT-Madrid



United States
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
UCLA
Drexel U.
U. Hawaii
IIT
Kansas State
LLNL
MIT
U. Notre Dame
SNL
U. Tennessee
Virginia Tech

Spokesperson: H. de Kerret (IN2P3) **Project manager:** Ch. Veyssi  re (CEA-Saclay)
Website: www.doublechooz.org

Double Chooz experiment



Designed to measure $\sin^2 2\theta_{13}$ via reactor $\bar{\nu}_e$ disappearance:

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{31}^2 L/E)$$

Site layout

Near detector

Overburden ≈ 120 mwe

Ready in mid-2014



Reactors

Two N4-type PWRs, 4.25 GW_{th} each

$\sim 1050\text{ m}$

Far detector

Overburden ≈ 300 mwe

Operating since April 2011



Inverse β decay signal

Prompt
signal:

e^+ scintillation and annihilation

$$E_{prompt} \approx E_{\bar{\nu}_e} - 0.8 \text{ MeV}$$



Delayed
signal:

n capture on Gd

$\hookrightarrow \gamma$ cascade

$$E_{delayed} \approx 8 \text{ MeV}$$

$$\Delta T \approx 30\mu\text{s}$$

OR

n capture on H

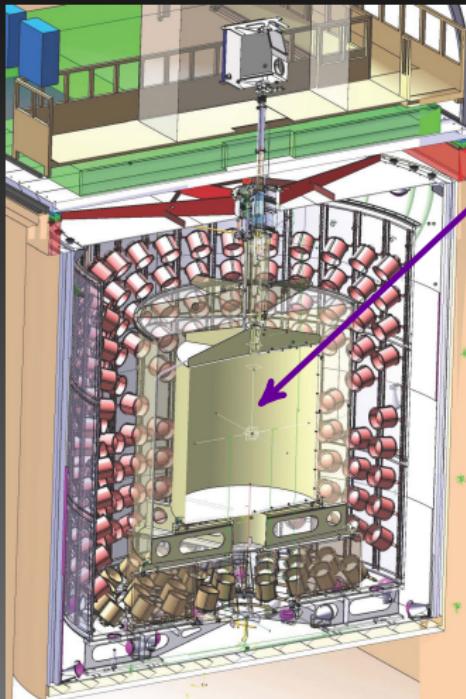
\hookrightarrow single γ

$$E_{delayed} = 2.2 \text{ MeV}$$

$$\Delta T \approx 200\mu\text{s}$$

Unique to Double Chooz!

Detector design

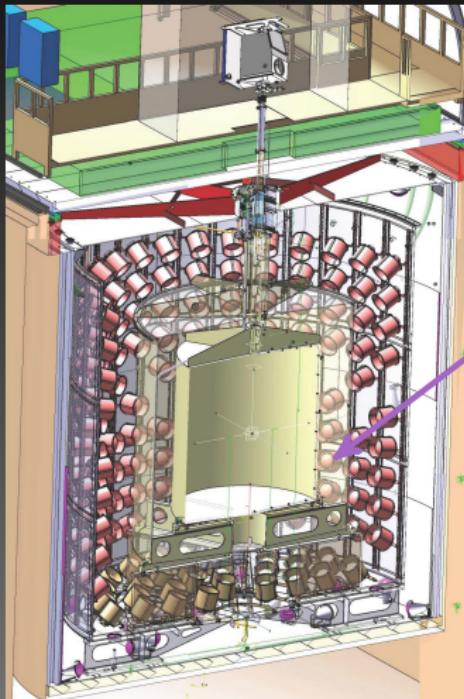


Inner detector:

Neutrino target

Gd-doped liquid scintillator (8.3 tons)

Detector design



Inner detector:

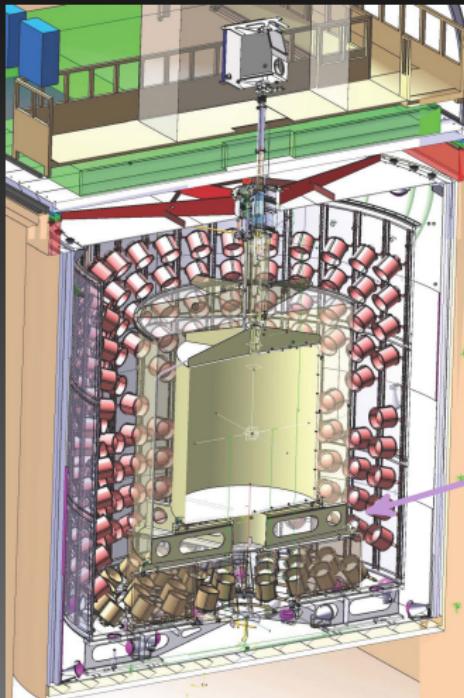
Neutrino target

Gd-doped liquid scintillator (8.3 tons)

Gamma catcher

Undoped liquid scintillator (18 tons)

Detector design



Inner detector:

Neutrino target

Gd-doped liquid scintillator (8.3 tons)

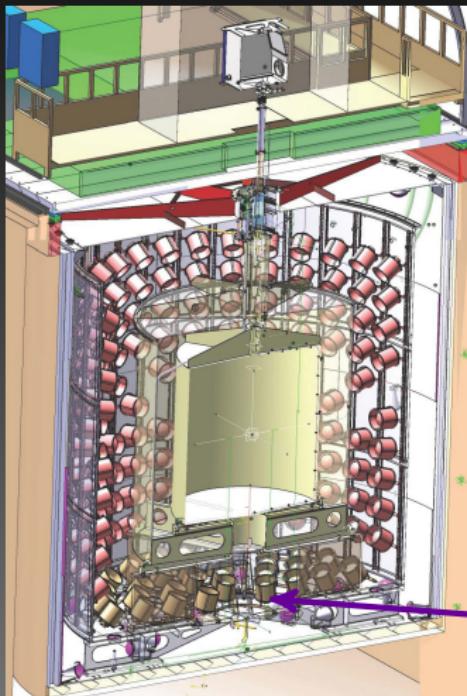
Gamma catcher

Undoped liquid scintillator (18 tons)

Buffer

Non-scintillating mineral oil (80 tons)

Detector design



Inner detector:

Neutrino target

Gd-doped liquid scintillator (8.3 tons)

Gamma catcher

Undoped liquid scintillator (18 tons)

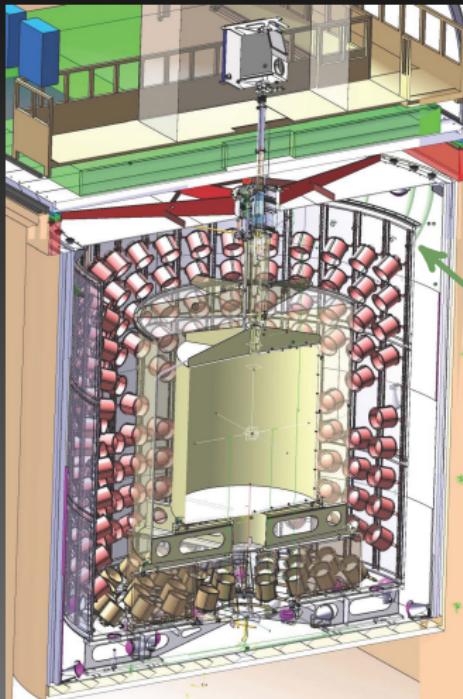
Buffer

Non-scintillating mineral oil (80 tons)

390 PMTs

installed on stainless steel tank

Detector design

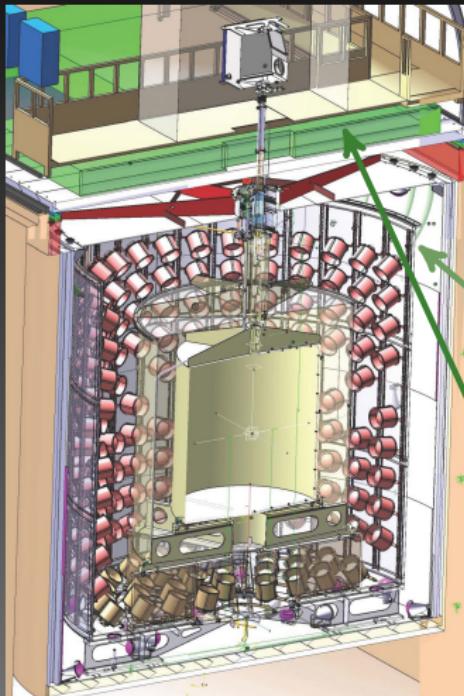


Cosmic ray veto systems:

Inner veto

Undoped liquid scintillator (70 tons)
+ 78 PMTs

Detector design



Cosmic ray veto systems:

Inner veto

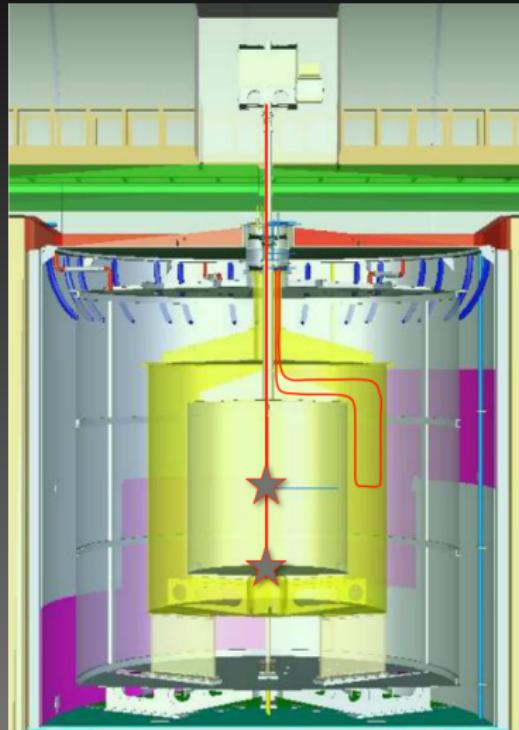
Undoped liquid scintillator (70 tons)
+ 78 PMTs

Outer veto

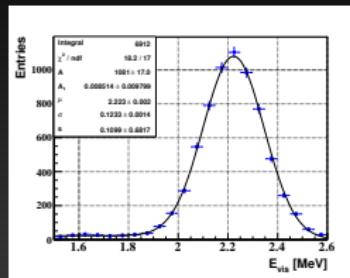
Array of plastic scintillator strips
13 m × 7 m

Calibration

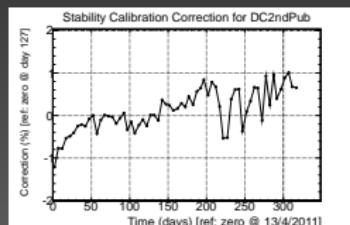
- ▶ **Source deployments:**
 ^{137}Cs , ^{68}Ge , ^{60}Co , ^{252}Cf
 - ▶ Z-axis
 - ▶ Guide tube
 - ▶ Fall 2014: Articulated arm
- ▶ **Spallation neutrons**
generated by cosmic rays
- ▶ **LED injection system**



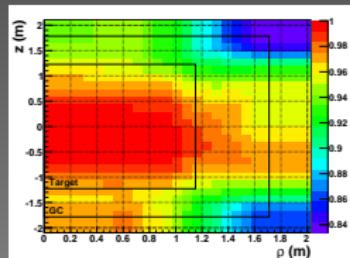
Energy reconstruction



- ▶ $q \rightarrow PE$, correcting for gain nonlinearity
 $PE \rightarrow MeV$, using H capture peak



- ▶ Correction for time instability,
using Gd capture peak variation



- ▶ Correction for detector inhomogeneity,
using H capture map

Signal selection

Parameter	Gd selection	H selection
E_{prompt}	0.7 – 12.2 MeV	0.7 – 12.2 MeV
E_{delayed}	6.0 – 12.0 MeV	1.5 – 3.0 MeV
ΔT	2 – 100 μs	10 – 600 μs
ΔR	—	< 90 cm

Further requirements for background reduction:		
Parameter	Gd selection	H selection
Multiplicity	No additional triggers in 500 μs surrounding prompt	No additional triggers in 1600 μs surrounding prompt
Muon veto	No muon in ID or IV in 1 ms before prompt	—
Showering muon veto	No muon depositing > 600 MeV in 0.5 s before prompt	—
OV veto	No OV hit coincident with prompt	—
Light noise rejection	Passes cuts on PMT charge isotropy & pulse simultaneity	—

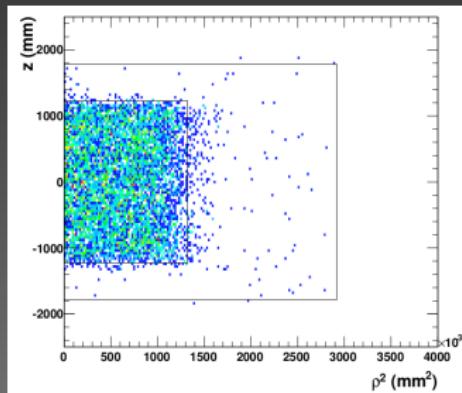
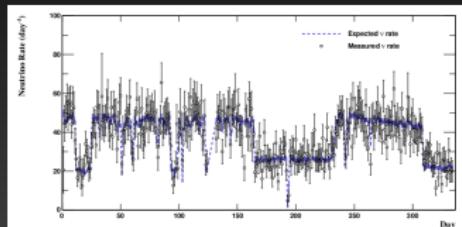
Predicted no-oscillation signal in April 2011–March 2012 dataset:

Gd selection: 8,440 H selection: 17,690

IBD candidates

Gd selection

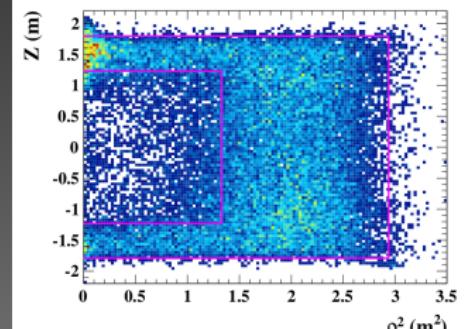
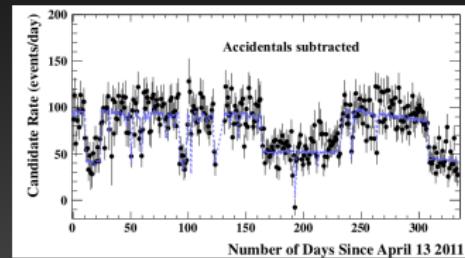
April 2011 – March 2012



Live time: 227.9 days
Candidates: 8,249

H selection

April 2011 – March 2012

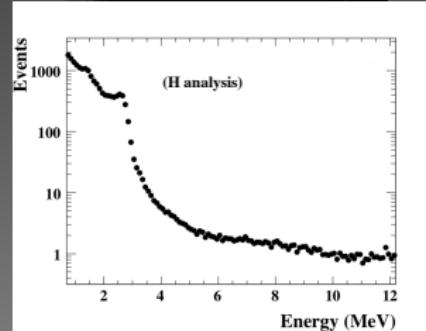


Live time: 240.1 days
Candidates: 36,284

Backgrounds

► Accidentals

- Gd: 0.3 d^{-1} (error $\ll 0.1 \text{ d}^{-1}$)
- H: $73.5 \pm 0.2 \text{ d}^{-1}$



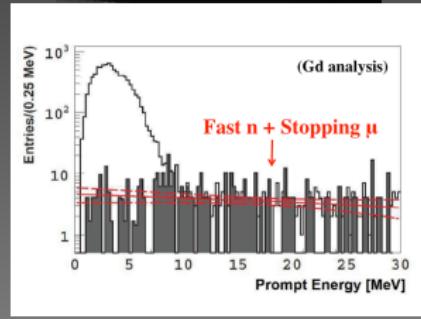
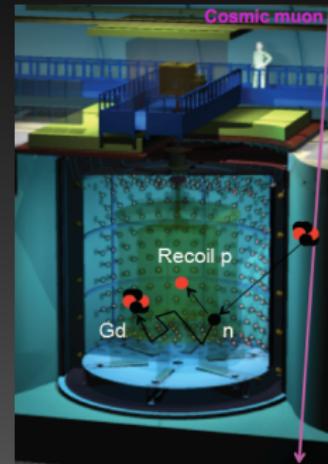
Backgrounds

► Accidentals

- Gd: 0.3 d^{-1} (error $\ll 0.1 \text{ d}^{-1}$)
- H: $73.5 \pm 0.2 \text{ d}^{-1}$

► Fast neutrons + stopping muons

- Gd: $0.7 \pm 0.2 \text{ d}^{-1}$
- H: $2.5 \pm 0.5 \text{ d}^{-1}$ (all fast n)



Backgrounds

► Accidentals

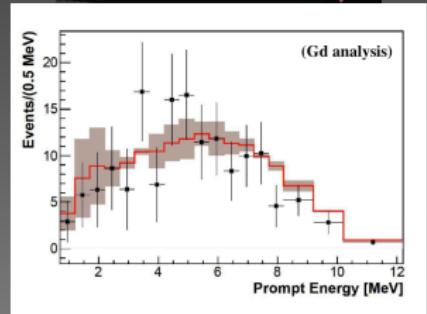
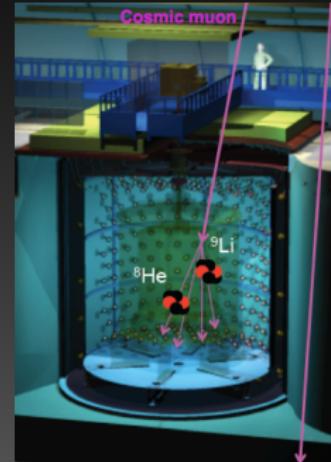
- Gd: 0.3 d^{-1} (error $\ll 0.1 \text{ d}^{-1}$)
- H: $73.5 \pm 0.2 \text{ d}^{-1}$

- Gd: $0.7 \pm 0.2 \text{ d}^{-1}$
- H: $2.5 \pm 0.5 \text{ d}^{-1}$ (all fast n)

► Cosmogenic isotopes, mainly ^9Li

- Gd: $1.3 \pm 0.5 \text{ d}^{-1}$
- H: $2.8 \pm 1.2 \text{ d}^{-1}$

Rates of ^9Li and FN + SM are further constrained in final fit.



$\bar{\nu}_e$ flux prediction

Far detector-only analyses rely on $\bar{\nu}_e$ rate prediction:

$$N = \frac{\epsilon N_p}{4\pi} \sum_{R=1,2} \frac{1}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \langle \sigma_f \rangle_R$$

- ϵ = detection efficiency
- N_p = number of protons in fiducial volume
- L_R = distance between reactor and far detector
- P_{th}^R = thermal power of reactor (time-dependent)
- $\langle E_f \rangle_R$ = average energy per fission (time-dependent)
- $\langle \sigma_f \rangle_R$ = average cross section per fission (time-dependent),
"anchored" to Bugey4 measurement at $L = 15$ m

Uncertainties

Normalization uncertainties (relative to signal):

Source	Gd selection	H selection
Reactor $\bar{\nu}_e$ flux	1.8%	1.8%
Efficiency	1.0%	1.6%
^9Li rate	1.5%	1.6%
Fast n + stopping μ rate	0.5%	0.6%
Accidentals rate	<0.1%	0.2%
Total statistical error	1.12%	1.08%

Spectrum shape uncertainties:

- ▶ Reactor $\bar{\nu}_e$ spectrum
- ▶ Energy scale
- ▶ ^9Li spectrum
- ▶ Fast n + stopping μ spectrum

Rate+Shape fit

Double Chooz fit strategy:

- ▶ Improves upon rate-based analysis by adding spectrum information
- ▶ Constrains backgrounds
- ▶ Fits data with specific oscillation shape

$$\chi^2_{\text{Rate+Shape}} = \sum_{i,j}^B \left(N_i^{\text{obs}} - N_i^{\text{pred}} \right) M_{ij}^{-1} \left(N_j^{\text{obs}} - N_j^{\text{pred}} \right)^T + \text{pull terms}$$

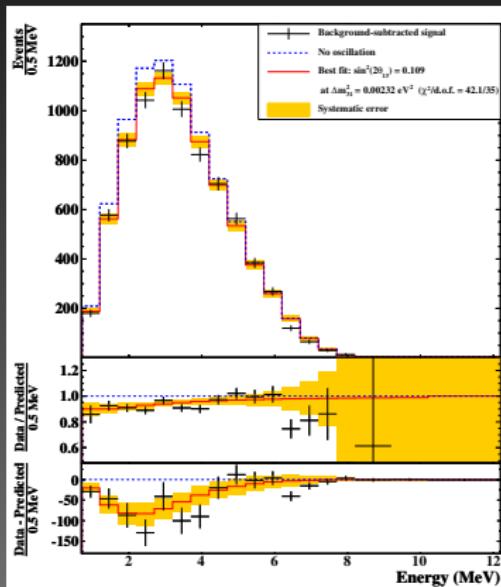
$$B = \text{number of energy bins} = \begin{cases} 18, & \text{for Gd} \\ 31, & \text{for H} \end{cases}$$

M = covariance matrix, including spectrum shape uncertainties

Pull terms on ${}^9\text{Li}$ rate, FN + SM rate, energy scale, Δm^2

Published Rate+Shape fits

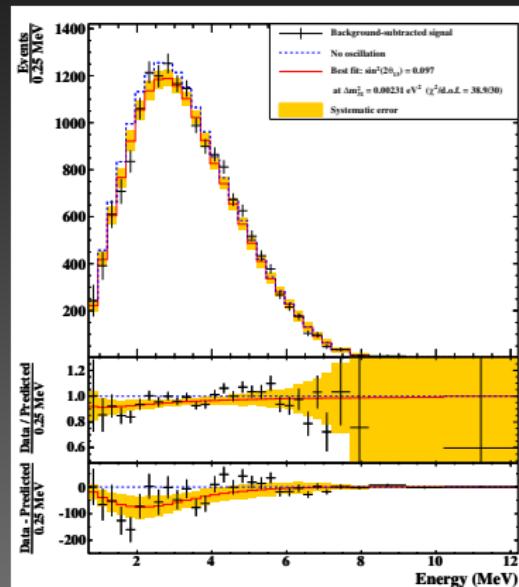
Gd analysis, June 2012 *Phys. Rev. D 86 (2012)*



$$\sin^2 2\theta_{13} = 0.109 \pm 0.039$$

Shown with all backgrounds subtracted. Gd uses two integration periods, yielding d.o.f. = $2 \times 18 - 1$

H analysis, December 2012 *Phys. Lett. B 723 (2013)*



$$\sin^2 2\theta_{13} = 0.097 \pm 0.048$$

Rate+Shape constraints

- Rate+Shape fit constrains backgrounds:

		Input (relative uncertainty)		Fit output (rel. unc.)
Gd	${}^9\text{Li}$ rate	$1.3 \pm 0.5 \text{ d}^{-1}$ (40%)	→	$1.0 \pm 0.3 \text{ d}^{-1}$ (30%)
	FN + SM rate	$0.7 \pm 0.2 \text{ d}^{-1}$ (30%)	→	$0.6 \pm 0.1 \text{ d}^{-1}$ (20%)
H	${}^9\text{Li}$ rate	$2.8 \pm 1.2 \text{ d}^{-1}$ (40%)	→	$3.9 \pm 0.6 \text{ d}^{-1}$ (15%)
	FN + SM rate	$2.5 \pm 0.5 \text{ d}^{-1}$ (20%)	→	$2.6 \pm 0.4 \text{ d}^{-1}$ (15%)

- Also adjusts energy scale and Δm^2 to reach best fit.

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- ▶ Reactor-off background measurements
- ▶ First combined Gd+H fit
- ▶ Reactor rate modulation analysis

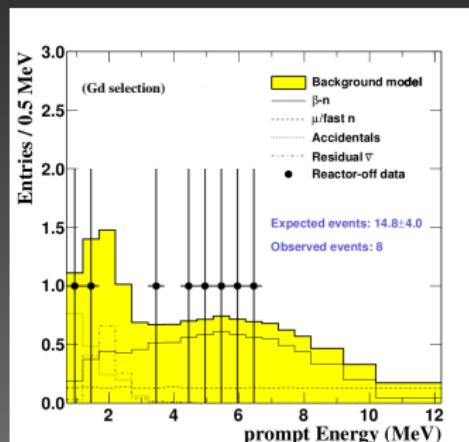
III. Future of Double Chooz

Reactor-off background measurements

Analyzed 7.5 days of data with both reactors off.

Phys. Rev. D. 87 (2013)

- ▶ Unique Double Chooz capability
- ▶ Rate consistent with predictions:
 - ▶ Gd selection: $1.0 \pm 0.4 \text{ day}^{-1}$
with residual $\bar{\nu}_e$ subtracted
(expected $2.0 \pm 0.6 \text{ day}^{-1}$)
 - ▶ H selection: $11.3 \pm 3.4 \text{ day}^{-1}$
with residual $\bar{\nu}_e$ and accidentals subtracted
(expected $5.8 \pm 1.3 \text{ day}^{-1}$)
- ▶ New constraint for oscillation fits



First combined Gd+H fit

Combining published Gd and H analyses:

- ▶ Data set covers April 2011–March 2012
- ▶ Fit includes correlation of systematic errors
- ▶ Backgrounds constrained by reactor-off measurements

Combined Gd+H fit results

PRELIMINARY:

Rate+Shape:	$\sin^2 2\theta_{13} = 0.109 \pm 0.035$	$(\chi^2/\text{d.o.f.} = 61.2/50)$
Rate-Only:	$\sin^2 2\theta_{13} = 0.107 \pm 0.045$	$(\chi^2/\text{d.o.f.} = 6.1/3)$

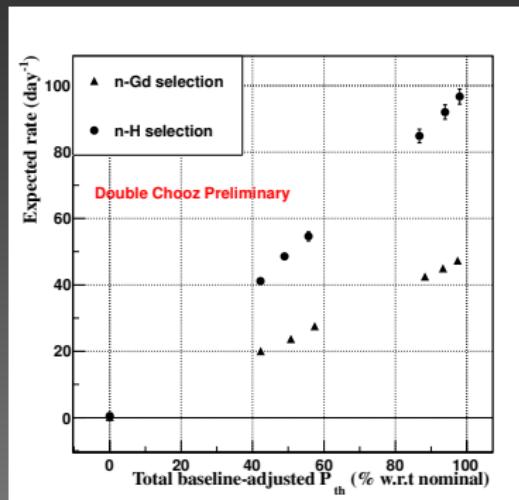
Compare to Gd analysis, June 2012:

Rate+Shape:	$\sin^2 2\theta_{13} = 0.109 \pm 0.039$	$(\chi^2/\text{d.o.f.} = 42.1/35)$
Rate-Only:	$\sin^2 2\theta_{13} = 0.170 \pm 0.052$	$(\chi^2/\text{d.o.f.} = 0.5/1)$

Reactor rate modulation analysis

Fit observed rates for $\sin^2 2\theta_{13}$ and total background rate, B:

$$R^{obs} = B + (1 - \sin^2 2\theta_{13} (\sin^2(1.27\Delta m^2 L/E))) R^{exp, no osc}$$

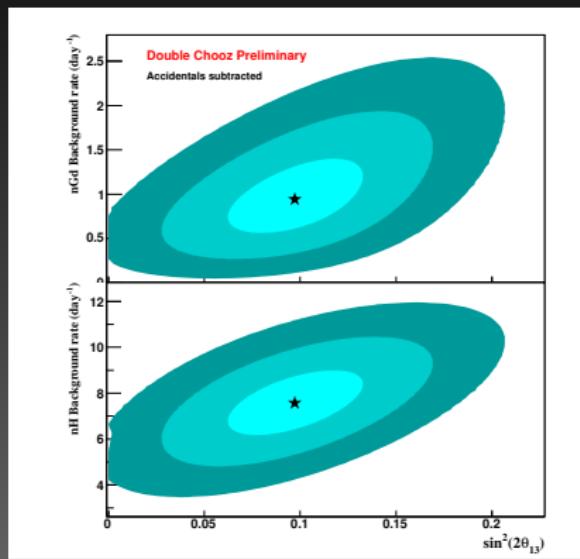
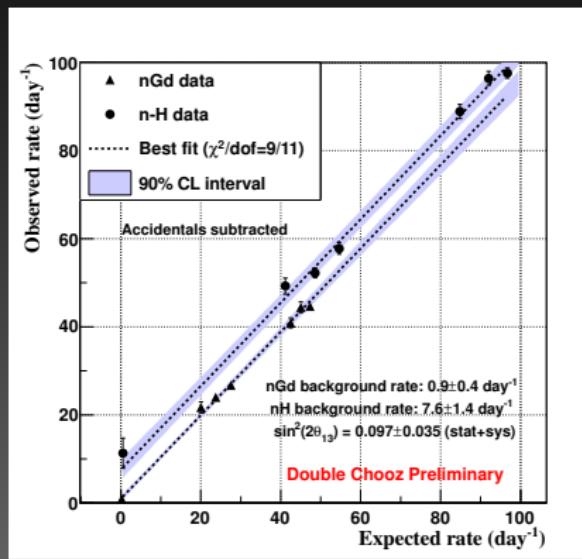


Valuable features:

- ▶ No *a priori* background model
- ▶ Combines Gd and H datasets
- ▶ Leverage from reactor-off data

For more details see P. Novella talk

Reactor rate modulation results



Best fit: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$

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Near detector

Near Detector Construction is ongoing



Near detector will begin taking data in 2014.

Future θ_{13} results

Expanded far detector-only analysis (end of 2013)

- ▶ $\sim 2\times$ more statistics + optimized selection
- ▶ Reduced systematic errors
- ▶ Projected precision: $\sigma \approx 0.03$

Two-detector analysis (2014)

- ▶ Reactor uncertainties nearly drop out
- ▶ Projected final precision: $\sigma \approx 0.01$

Summary

- ▶ **Rich, unique program with far detector**
 - ▶ Rate+Shape fits - first result in 2011
 - ▶ Two signal channels Gd+H used in the analysis
 - ▶ Reactor-off background measurements (unique capability)
 - ▶ Reactor rate modulation analysis (RRM)

Summary

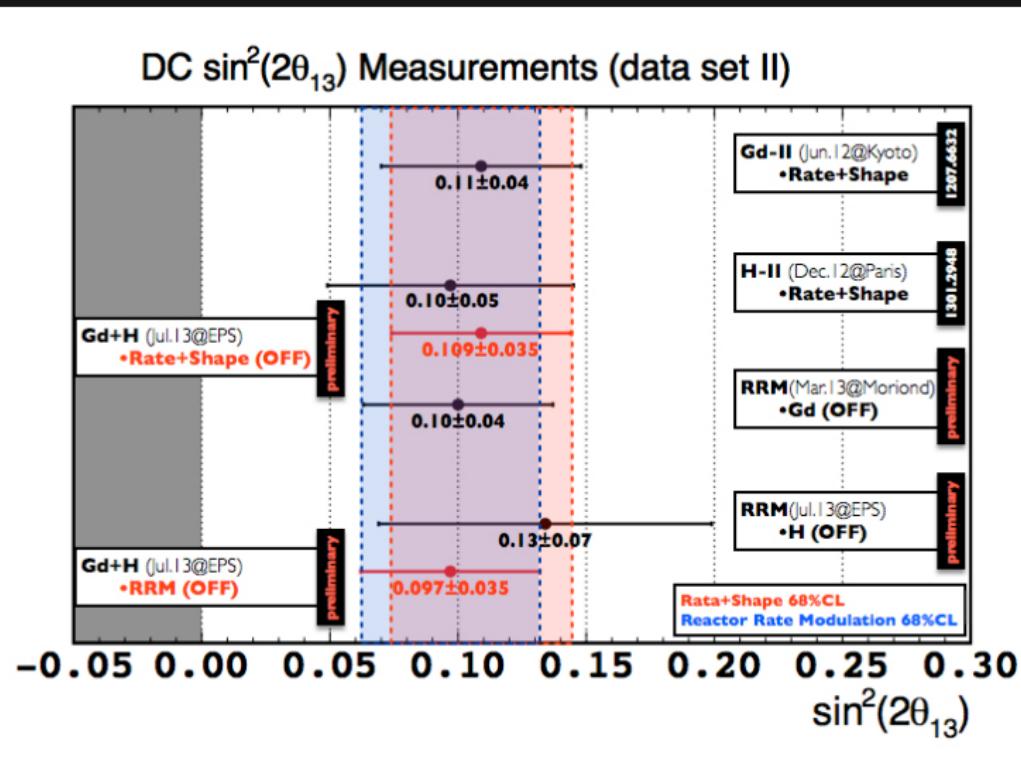
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- ▶ New results
 - ▶ Gd+H Rate+Shape fit: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$
 - ▶ Reactor rate modulation: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$

Summary

- ▶ **Rich, unique program with far detector**
 - ▶ Rate+Shape fits - first result in 2011
 - ▶ Two signal channels Gd+H used in the analysis
 - ▶ Reactor-off background measurements (unique capability)
 - ▶ Reactor rate modulation analysis (RRM)
- ▶ **New results**
 - ▶ Gd+H Rate+Shape fit: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$
 - ▶ Reactor rate modulation: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$
- ▶ **Future prospects**
 - ▶ Improved single-detector analysis
 - ▶ First two-detector analysis

Backup

Summary of Double Chooz results



Gd, H, and combined fit results

Rate+Shape:

Fit parameter	Individual fit results		Combined fit, Jul. 2013	
	Gd, Jun. 2012	H, Dec. 2012	Gd selection	H selection
Energy scale	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01
FN+SM rate (d^{-1})	0.6 ± 0.1	2.6 ± 0.4	0.6 ± 0.1	2.6 ± 0.4
Li-9 rate (d^{-1})	1.0 ± 0.3	3.9 ± 0.6	0.9 ± 0.2	3.9 ± 0.6
Δm^2 ($10^{-3} eV^2$)	2.32 ± 0.12	2.32 ± 0.12	2.31 ± 0.12	
$\sin^2 2\theta_{13}$	0.109 ± 0.039	0.097 ± 0.048	0.109 ± 0.035	
$\chi^2/d.o.f.$	42.1/35	38.9/30	61.2/50	

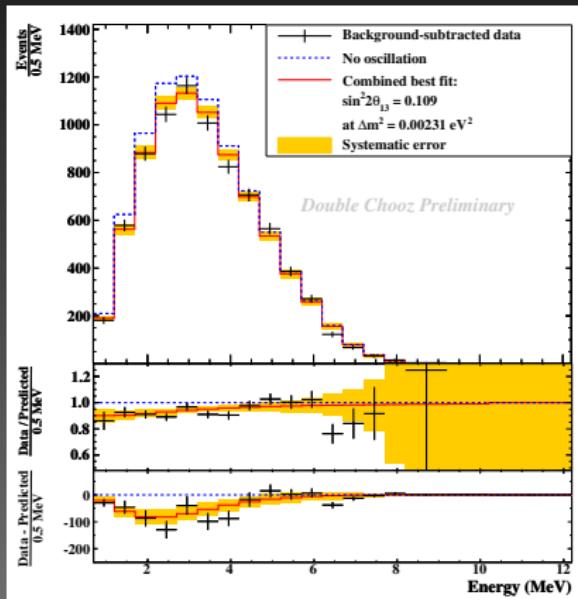
Rate-Only:

Fit parameter	Individual fit results		Combined fit, Jul. 2013	
	Gd, Jun. 2012	H, Dec. 2012	Gd selection	H selection
Energy scale	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01	1.00 ± 0.02
FN+SM rate (d^{-1})	0.7 ± 0.2	2.5 ± 0.5	0.6 ± 0.2	2.7 ± 0.5
Li-9 rate (d^{-1})	1.4 ± 0.5	2.8 ± 1.2	0.8 ± 0.4	3.7 ± 1.0
Δm^2 ($10^{-3} eV^2$)	2.32 ± 0.12	2.32 ± 0.12	2.32 ± 0.12	
$\sin^2 2\theta_{13}$	0.170 ± 0.052	0.044 ± 0.061	0.107 ± 0.045	
$\chi^2/d.o.f.$	0.5/1	0/0	6.1/3	

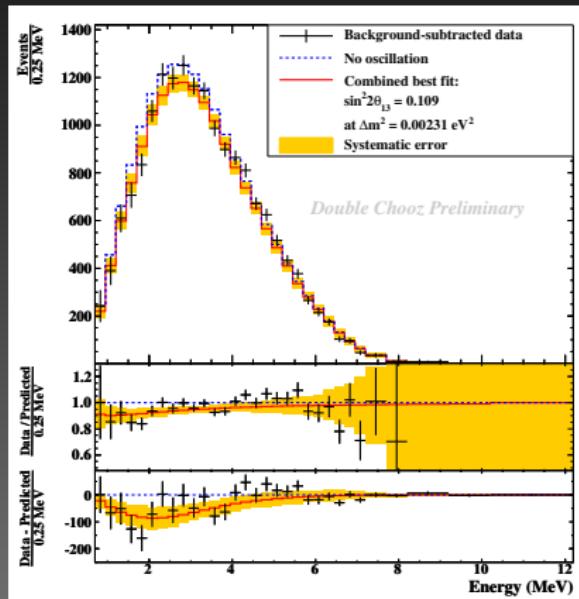
Reactor-off information is not included in individual fits.

Combined Gd+H Rate+Shape fit

Gd selection



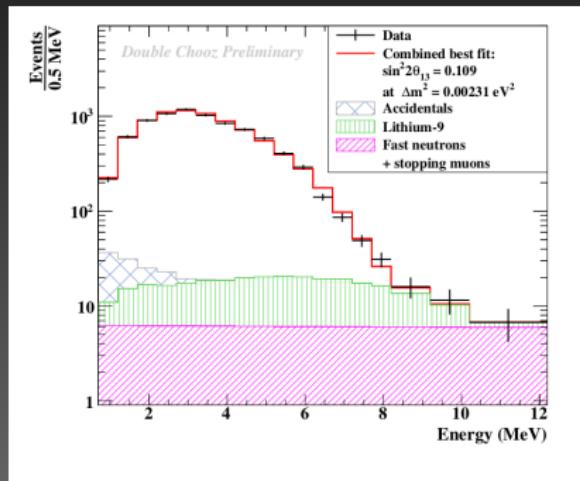
H selection



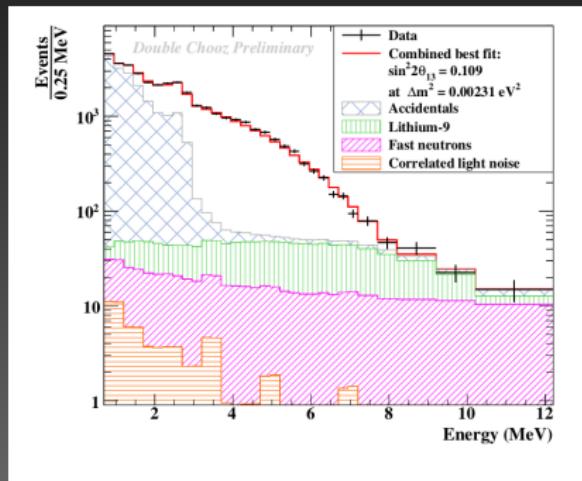
All backgrounds subtracted at best-fit rates.

Gd and H prompt spectra, with backgrounds

Gd selection



H selection



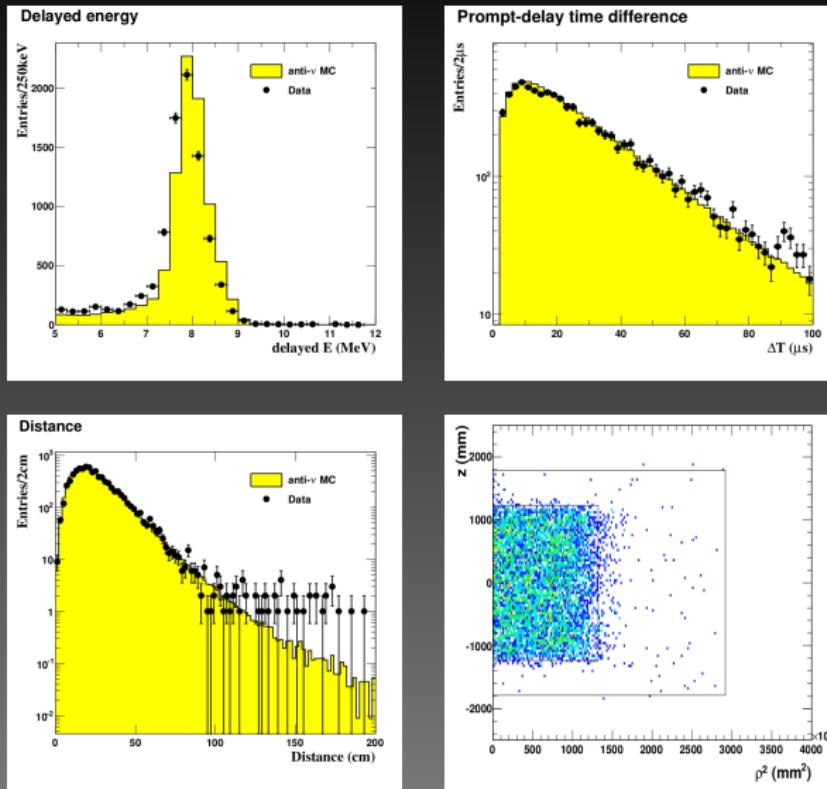
Red line is combined Gd+H Rate+Shape best fit.
Backgrounds shown at best-fit rates.

Correlations between Gd and H analyses

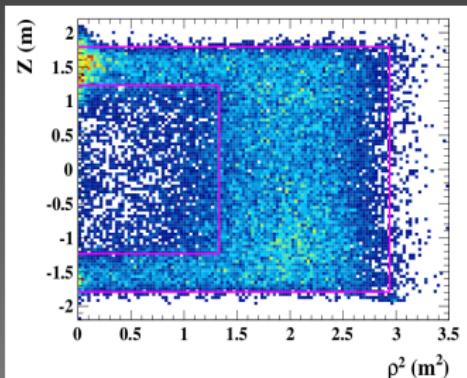
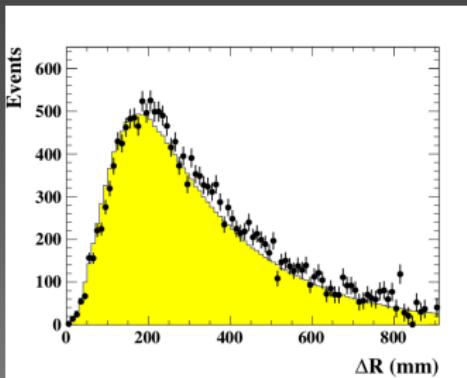
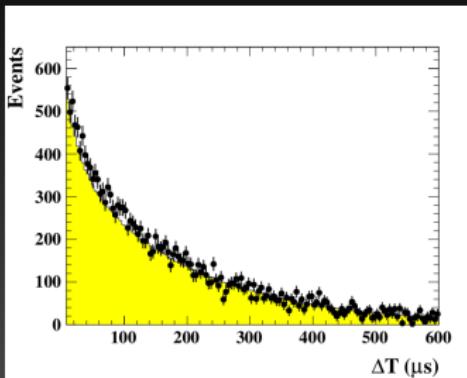
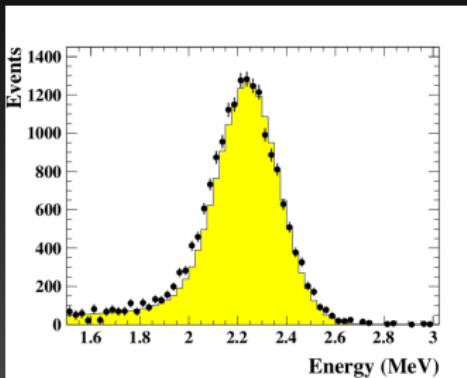
PRELIMINARY

Parameter	$\rho_{Gd,H}$
Accidental rate	0
Correlated light noise	0
Fast n + stopping μ rate	0
${}^9\text{Li}$ rate	0.003
${}^9\text{Li}$ shape	1
Efficiency	0.09
Energy scale	0.4
Reactor	1

Candidates from Gd selection



Candidates from H selection



χ^2 definition for individual Gd and H fits

$$\begin{aligned}\chi^2_{Rate+Shape} = & \sum_{i,j}^B \left(N_i^{obs} - N_i^{pred} \right) M_{ij}^{-1} \left(N_j^{obs} - N_j^{pred} \right)^T \\ & + \frac{(\alpha_{Li} - 1)^2}{\sigma_{Li}^2} + \frac{(\alpha_{FNSM} - 1)^2}{\sigma_{FNSM}^2} + \frac{(\alpha_E - 1)^2}{\sigma_E^2} \\ & + \frac{(\Delta m^2 - \Delta m_{MINOS}^2)^2}{\sigma_{MINOS}^2}\end{aligned}$$

with covariance matrix:

$$M = M_{stat} + M_{reactor} + M_{acc} + M_{corr\ LN} + M_{Li\ shape} + M_{FNSM\ shape}$$

χ^2 definition for combined Gd+H fit

$$\chi^2 = \sum_{i,j}^B (N_i^{obs} - N_i^{pred}) M_{ij}^{-1} (N_j^{obs} - N_j^{pred}) \quad (1)$$

Inner product with covariance matrix, as defined on previous slide

$$+ \frac{(\Delta m^2 - \Delta m_{MINOS}^2)^2}{\sigma_{MINOS}^2} \quad (2) \quad \text{Mass splitting pull term}$$

$$+ \left[(\alpha_{li}^{Gd} - 1), (\alpha_{fn}^{Gd} - 1), (\alpha_e^{Gd} - 1), (\alpha_{li}^H - 1), (\alpha_{fn}^H - 1), (\alpha_e^H - 1) \right] \\ \times \begin{bmatrix} (\sigma_{li}^{Gd})^2 & 0 & 0 & \rho_{li}\sigma_{li}^{Gd}\sigma_{li}^H & 0 & 0 \\ 0 & (\sigma_{fn}^{Gd})^2 & 0 & 0 & \rho_{fn}\sigma_{fn}^{Gd}\sigma_{fn}^H & 0 \\ 0 & 0 & (\sigma_e^{Gd})^2 & 0 & 0 & \rho_e\sigma_e^{Gd}\sigma_e^H \\ \rho_{li}\sigma_{li}^H\sigma_{li}^{Gd} & 0 & 0 & (\sigma_{li}^H)^2 & 0 & 0 \\ 0 & \rho_{fn}\sigma_{fn}^H\sigma_{fn}^{Gd} & 0 & 0 & (\sigma_{fn}^H)^2 & 0 \\ 0 & 0 & \rho_e\sigma_e^H\sigma_e^{Gd} & 0 & 0 & (\sigma_e^H)^2 \end{bmatrix}^{-1} \\ + \left[(\alpha_{li}^{Gd} - 1), (\alpha_{fn}^{Gd} - 1), (\alpha_e^{Gd} - 1), (\alpha_{li}^H - 1), (\alpha_{fn}^H - 1), (\alpha_e^H - 1) \right] \quad (3)$$

Correlated pull terms on background rates and energy scale

$$+ \left[(\alpha_{li}^{Gd} R_{li}^{Gd,pred} + \alpha_{fn}^{Gd} R_{fn}^{Gd,pred} - R_{off}^{Gd}), (\alpha_{li}^H R_{li}^{H,pred} + \alpha_{fn}^H R_{fn}^{H,pred} - R_{off}^H) \right] \\ \times \begin{bmatrix} (\sigma_{off}^{Gd})^2 & \rho_{off}\sigma_{off}^{Gd}\sigma_{off}^H \\ \rho_{off}\sigma_{off}^H\sigma_{off}^{Gd} & (\sigma_{off}^H)^2 \end{bmatrix}^{-1} \times \begin{bmatrix} (\alpha_{li}^{Gd} R_{li}^{Gd,pred} + \alpha_{fn}^{Gd} R_{fn}^{Gd,pred} - R_{off}^{Gd}) \\ (\alpha_{li}^H R_{li}^{H,pred} + \alpha_{fn}^H R_{fn}^{H,pred} - R_{off}^H) \end{bmatrix} \quad (4)$$

Reactor-off rate constraints

Predicted $\bar{\nu}_e$ spectrum

$$N_i = \frac{\epsilon N_p}{4\pi} \sum_R \frac{1}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \left(\frac{\langle \sigma_f \rangle_R}{\sum_k \alpha_k^R \langle \sigma_f \rangle_k} \sum_k \alpha_k^R \langle \sigma_f \rangle_k^i \right)$$

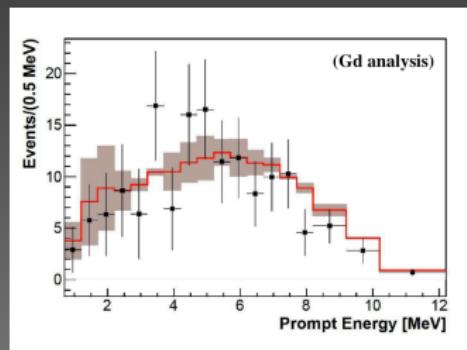
Bugey4 “anchor”: $\langle \sigma_f \rangle_R = \sigma_f|_{Bugey} + \sum_k (\alpha_k - \alpha_k^{Bugey}) \langle \sigma_f \rangle_k$
scales predicted $\langle \sigma_f \rangle$ to match $\langle \sigma_f \rangle$ measured at $L = 15$ m,
removing sensitivity to $\Delta m^2 \sim 1$ eV² oscillations

R	=	{Reactor 1, Reactor 2}
k	=	{ ²³⁵ U, ²³⁸ U, ²³⁹ P, ²⁴¹ P}
ϵ	=	detection efficiency
N_p	=	number of protons in fiducial volume
L_R	=	distance between R^{th} reactor and far detector
P_{th}^R	=	thermal power of R^{th} reactor (time-dependent)
$\langle E_f \rangle_R$	=	mean energy per fission in R^{th} reactor (time-dependent)
$\langle \sigma_f \rangle_R$	=	mean cross section per fission in R^{th} reactor (time-dependent)
α_k^R	=	fission fraction for k^{th} isotope in R^{th} reactor (time-dependent)
$\langle \sigma_f \rangle_k$	=	mean cross section per fission of k^{th} isotope
$\langle \sigma_f \rangle_k^i$	=	mean cross section per fission of k^{th} isotope in i^{th} energy bin

${}^9\text{Li}$ measurement

Rate derived from $\Delta t_\mu = t - t_{\text{previous } \mu}$ for IBD candidates:

- ▶ Δt_μ distribution fit with $\tau({}^9\text{Li}) = 257$ ms
- ▶ Sample purity increased with cuts on $\Delta R_{\mu \text{ track}}$
- ▶ Consistent rates derived from Gd and H selections



Spectrum shape predicted from MC:

- ▶ Spectrum uncertainties from uncertainty on ${}^9\text{Li}$ branching ratios
- ▶ Consistent shape seen in data